A new charged particle detector for the KOTO experiment at J-PARC

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Abstract. We installed a new detector called Downstream Charged Veto(DCV) in order to suppress the $K_L \to \pi^+\pi^-\pi^0$ decay background for the J-PARC KOTO experiment. Since the background is caused by non-detected charged pions passing through the beam hole of the electromagnetic calorimeter, the detector was installed in vacuum right behind. The DCV is composed of two plastic scintillator pipes read out by Multi Pixel Photon Counter(MPPC)s through wavelength shifting(WLS) fibers. From the test by using cosmic-rays during its fabrication, we obtained about 60 photoelectrons at the center of the DCV is about 60. After its installation, energy calibration was done with cosmic-rays surrounding the K_L beam, and its signal is identified by detectors surrounding the DCV.

1. Introduction

The KOTO experiment at J-PARC is searching for the $K_L \to \pi^0\nu\bar{\nu}$ decay, which is one of the most sensitive probes to new physics beyond the standard model(SM). Its signature is a pair of photons from a π^0 decay without any additional activity in a hermetic detector system surrounding the decay region. To detect this highly suppressed decay, expected at the 3×10^{-11} level, it is important to reject background events related to other kaon decay modes. At the single event sensitivity of 1.30×10^{-9} achieved by data collected in 2015, the number of $K_L \to \pi^+\pi^-\pi^0$ background was estimated as 0.05 ± 0.02 which corresponds to 2 at the SM sensitivity. The decay becomes background when charged pions passing through the beam hole are not detected due to their interaction with non-active materials. According to a Monte Carlo(MC) simulation, as shown in Fig. 1, there are three materials where the π^+ and π^- interact and disappear. One is the membrane which separate decay region be evacuated as 10^{-5} Pa from the detector region where is relatively low level of vacuum(10^{-2} Pa). The other source is a pipe made of 0.5-mm-thick G-10, which prevents the membrane from drooping down to beam. The last one is a beam pipe made of 10-mm-thick aluminum for extending the highly evacuated decay region far from the calorimeter. Since the DCV is able to support the membrane, we need not the G-10 pipe anymore.(The G-10 pipe inside the calorimeter is remained, however, its length was shortened.)

To reduce the $K_L \to \pi^+\pi^-\pi^0$ background events, we have to detect the charged pions before they interact with non-active materials. For the purpose, we decided to install a new charged particle detector, DCV, inside a high vacuum region downstream of the electromagnetic calorimeter. To minimize the non-detected area, the DCV is placed as close as possible to the electromagnetic calorimeter.

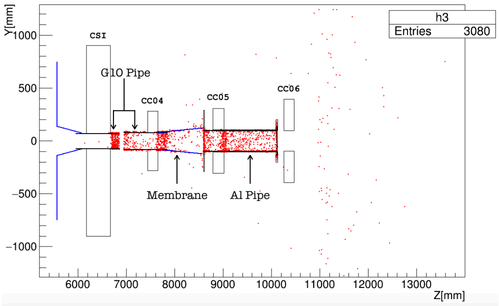


Figure 1. Interacting point with π^+ and π^-. Red dots indicate where the charged pions disappeared.

2. Structure of the DCV

The DCV consists of two successive square pipes, and each of them is made of 4 sheets of scintillators combined. The DCV1 is placed at 463 mm downstream from the calorimeter and inside the membrane. The DCV1 is a trapezoidal pipe, and the length of its upstream side is 157.5 mm and its downstream side is 171.5 mm. The beam direction length is 1410 mm. The DCV2 is placed at 76 mm downstream from the DCV1 and inside the aluminum beam pipe. The DCV2 is a square pipe, and the length of its upstream and downstream side is 173.5 mm. The beam direction length is 1460 mm. We made 18 grooves in a 5-mm-thick plastic scintillator (EJ200, Eljen Technology) in order to embedded 1 mm diameter WLS fibers(Y-11(200M), Kuraray). For the light collection in the very limited space, the WLS fibers are routed into a light guide made of aluminum at the scintillator surface. Since the size of the light guide is 6 mm $\times$ 6 mm to fit the size of MPPC, the WLS fibers are needed to be bent to converge into the light guide as shown in Fig. 2. The light loss due to the curvature shows a rapid increase when the radius is smaller than 20 mm as shown in Fig. 3, which is a design principle for the grooves. The WLS fibers are grouped into two parts and read by MPPC(S13360-6050PE, Hamamatsu) at both ends of each part(4 read-out MPPCs in total).

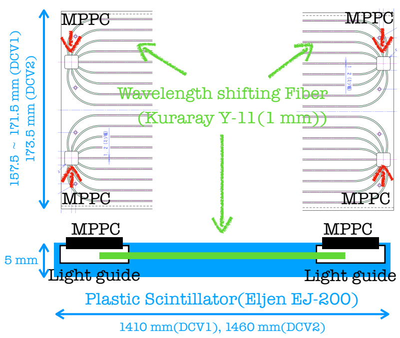


Figure 2. Scheme of the DCV.

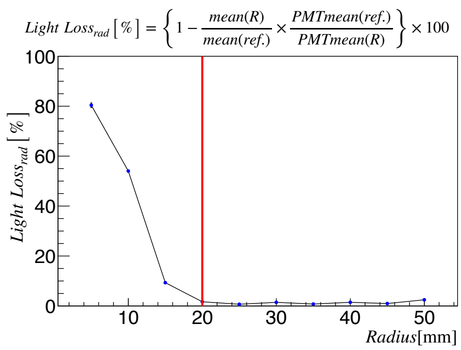


Figure 3. The light loss due to the curvature of the WLS fiber. The radius is a parameter of curvature. We measured the light yield by MPPC of the LED light(430 mm) passing through the bent fiber. The light consistency was measured using PMT before injecting LED light into the fiber.

3. Fabrication Process

3.1. MPPC Gain Measurement and Fiber Test

The 4 MPPCs belonging to each scintillator plate were applied the same operating voltage. To group the MPPCs into four similar gain sets, we measured the MPPCs single-photon gain using the LED light(430 nm). We also measured the light yield of the WLS fibers. The LED light(430 nm) was injected on one side of the flagged WLS fiber that we assigned before, and the MPPC was attached on the other side. After the measurement of the light yield, we chose the WLS fiber with a high light yield.

3.2. Making the scintillator pipe

First, the WLS fibers were glued to the plastic scintillator using the optical cement(BC-600, Saint-Gobain). The scintillators were dried for at least 48 hours. Second, the scintillators were placed in a vacuum chamber. We extracted the outgas from the glued scintillators at less than 1 Pa, over 48 hours. Third, the scintillators were wrapped by a 12-μm-thick aluminized film. Next, the MPPCs were respectively attached on the light guide and fixed by aluminum plates. After the cosmic-ray test, the scintillators were assembled to a square pipe.

3.3. Cosmic-ray test

To evaluate the light yield of the DCV, we measured the number of p.e. using cosmic-rays at 8 points, as shown in Fig. 4. At the center, the average number of p.e. for 1 MeV was 60.2 for the DCV1 and 58.6 for the DCV2. By fitting the data with an exponential function, the attenuation length was found to be 2469 ± 165.1 mm for the DCV1 and 2566 ± 166.0 mm for the DCV2.

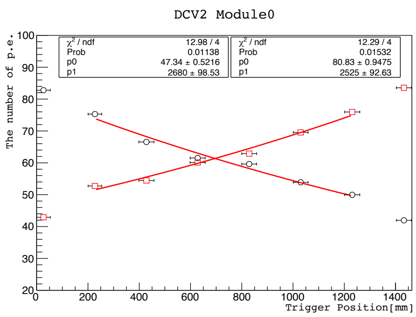


Figure 4. The number of p.e. at each cosmic-ray trigger point

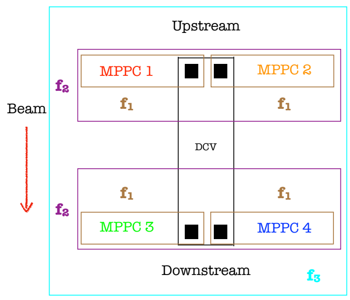
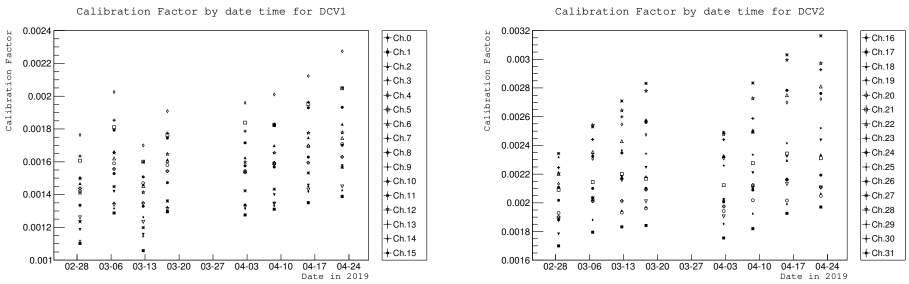


Figure 5. Calibration method for the DCV with 4 MPPCs. There are 3 types of normalization factors(f_1 : for each MPPC, f_2 : for a pair of MPPC at upstream(downstream), f_4 : for all MPPCs).

4. Energy Calibration

After the installation of the DCV in the KL beamline, we took the cosmic-ray data for an energy calibration. The CC04 and CC05 surrounding the DCV were used as the trigger counter. Figure 5 shows the diagram of the calibration method for the DCV with 4 MPPCs which were shared one energy deposit. The energy response to the cosmic-ray of each module of the DCV was used to derive the 3 types of normalization factors. Each normalization factor was obtained from MIP peak by fitting the pulse height distribution. f_1 was derived from each MPPC. After the pulse height distribution of each MPPC is normalized, the pulse height from a pair of MPPCs at upstream or downstream was summed, and f_2 was derived from its distribution. After the pulse height distribution of a pair of MPPCs is normalized, the pulse height from 4 MPPCs in the same scintillator was summed, and f_3 was derived from its distribution. During the beam time from Feb. to Apr. 2019, we collected the cosmic-ray data. Figure 6 shows how the calibration factor varies during the period. The calibration factors tend to increase over time.



(a) (b)

Figure 6. Calibration Factor over time for DCV1(a) and DCV2(b).

5. Summary

We fabricated and installed a new charged particle detector, the DCV, for further rejection of the background events from the $K_L \rightarrow \pi^+\pi^-\pi^0$ decay. Based on the cosmic-ray test performed during its fabrication, the light yield is about 60 p.e. for 1 MeV at the center of the DCV. We established a method of its calibration by using cosmic-ray identified by detectors surrounding the DCV. The energy calibration was done for the MeV scale. Studies on stability of its performance during the beam time is undergoing.

Acknowledge

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Reference

[1] J.K. Ahn *et al.* (KOTO Collaboration) 2019, *Phys. Rev. Lett.* **122** 021802